Visions:

The Coming Revolutions in Particle Physics

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Fermilab

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Galileo's Three Revolutions

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Eppur si muove . . .

Galileo's Three Revolutions

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- Completing the Copernican Revolution

  Humans do not occupy a privileged location in the Universe

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Cimenti . . .

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▷ Rejecting Authority:

Learning to read Nature by doing experiments

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The minute particular . . .

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▷ Completing the Copernican Revolution

Humans do not occupy a privileged location in the Universe

Cimenti . . .

▷ Rejecting Authority:

Learning to read Nature by doing experiments

The minute particular . . .

▷ Not asking general questions and receiving limited answers,

but asking limited questions and finding general answers

Our Picture of Matter

Pointlike ($r \lesssim 10^{-18}$ m) **quarks**

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

and **leptons** (idealization that neutrinos are massless) ...

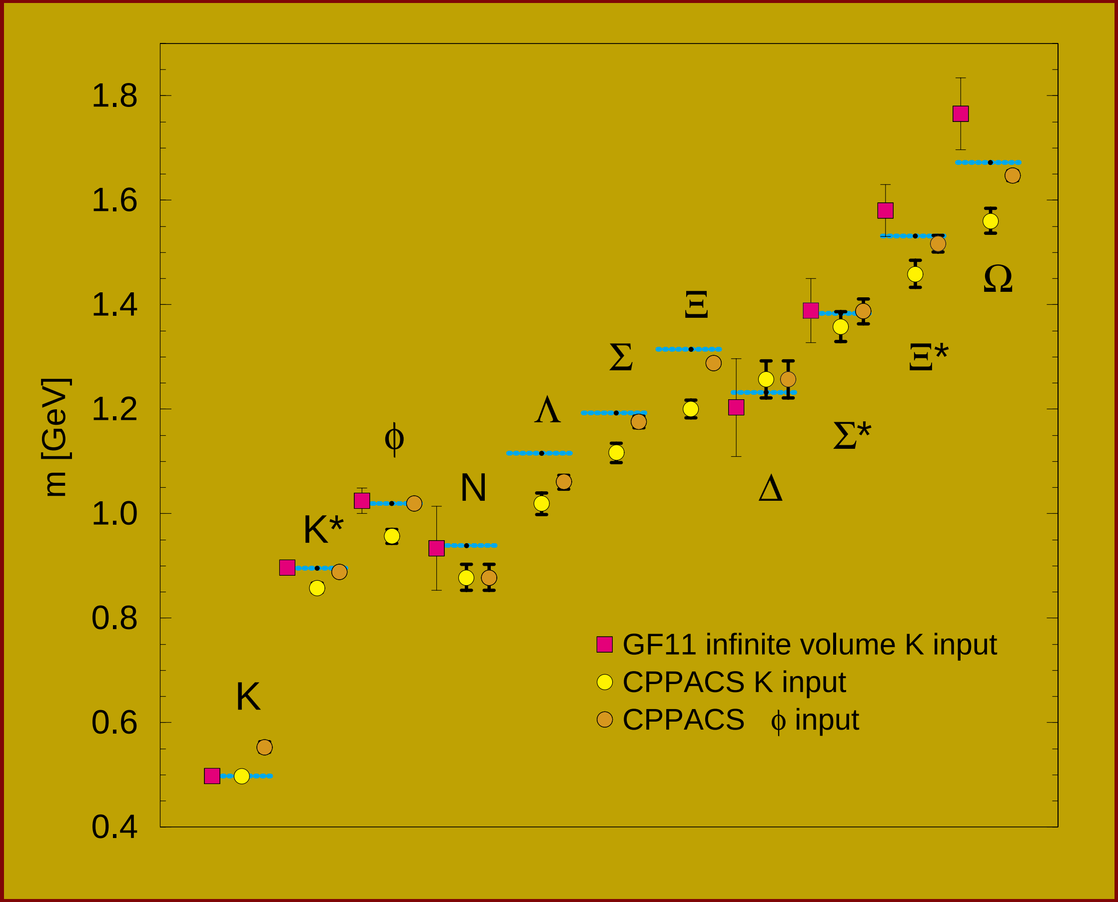
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

with interactions specified by

$$\mathbf{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y}$$

gauge symmetries ...

QCD explains the light hadron masses



For p, ρ, $[\pi]$, . . . , *confinement energy* is the source.

"Mass without mass"

From the 1898–99 University of Chicago catalogue:

"While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice . . . . An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals."

Electroweak theory has many successes

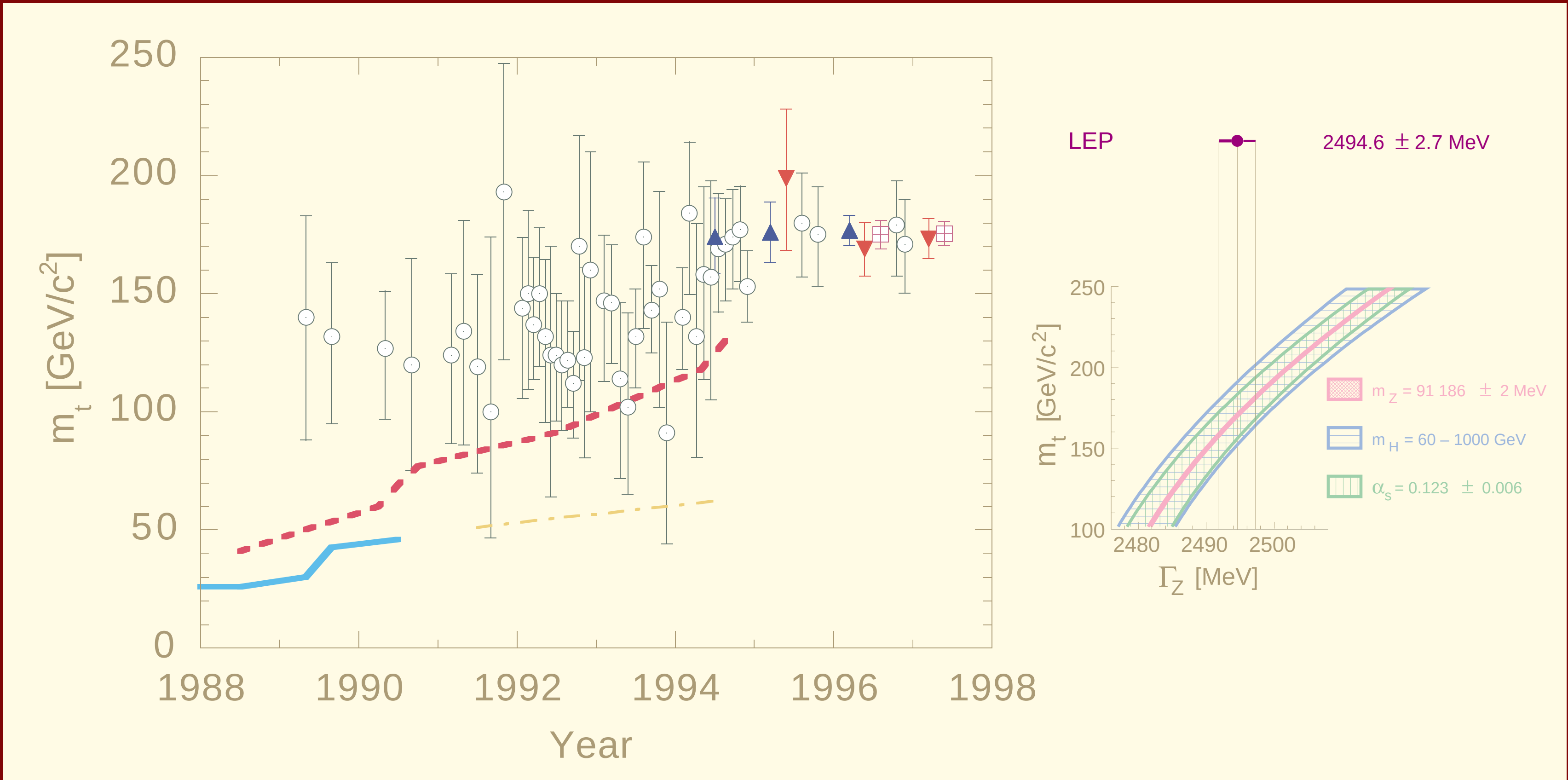
- Neutral currents
- Charm
- Weak gauge bosons $W^{\pm}$ and Z^0

A decade of LEP, et al.

- Testing the quantum field theory at the one per mille level
- Looking for new physics "in the sixth place of the decimals"

Precision measurements to determine unknown parameters . . .

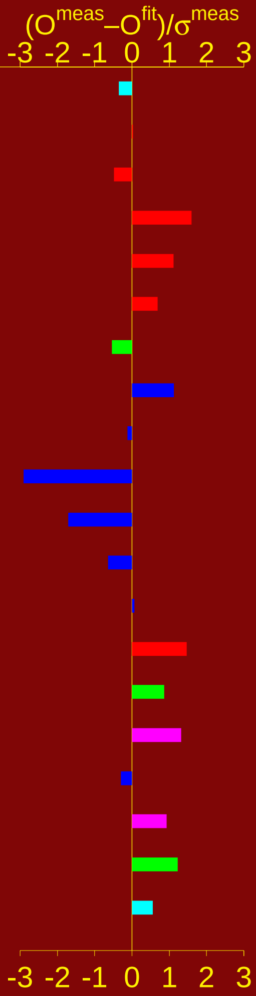
Inferring the top-quark mass through its rôle in quantum corrections:



Precision measurements test the theory . . .

Summer 2001

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ^0_{had} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.90
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
Q_W(Cs)	-72.50 ± 0.70	.56



The Result

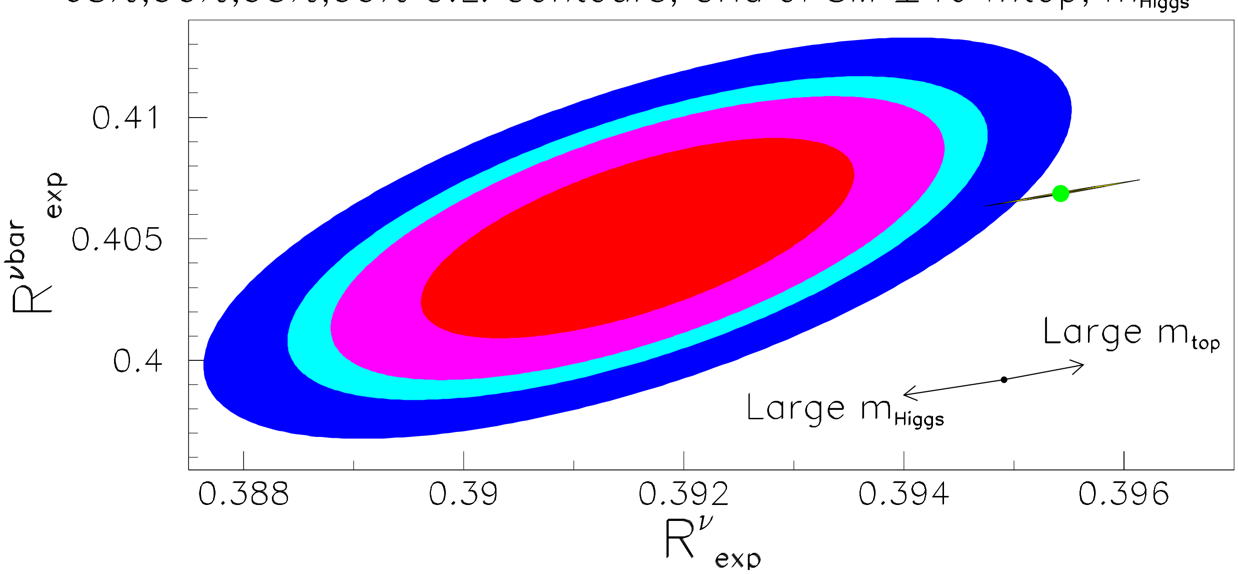
NuTeV Measures:

$$\begin{aligned}\sin^2\theta_W^{(\mathrm{on-shell})} &= 0.2277 \pm 0.0013(\mathrm{stat.}) \pm 0.0009(\mathrm{syst.}) \\ &- 0.00022\times\left(\frac{M_{\mathrm{top}}^2-(175\,\mathrm{GeV})^2}{(50\,\mathrm{GeV})^2}\right) \\ &+ 0.00032\times\ln\left(\frac{M_{\mathrm{Higgs}}}{150\,\mathrm{GeV}}\right)\end{aligned}$$

cf. standard model fit (LEPEWWG), 0.2227 ± 0.00037

A discrepancy of 3σ...

68%,90%,95%,99% C.L. Contours, Grid of SM ±1σ mtop, m_{Higgs}



R^{ν}_{exp} and $R^{\overline{\nu}}_{\mathrm{exp}}$ measured to a precision of 0.3%, 0.65%, respectively

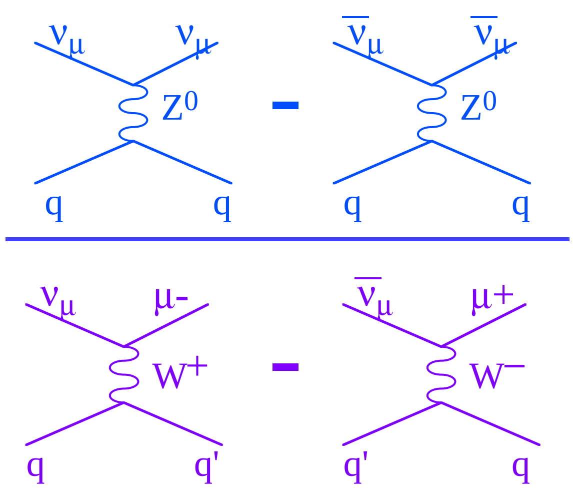
(systematics lead to correlated uncertainty)

NuTeV's Technique

Charm Production and Charm Sea Errors are Large
$\Rightarrow$ Need a Technique Insensitive to Sea Quarks

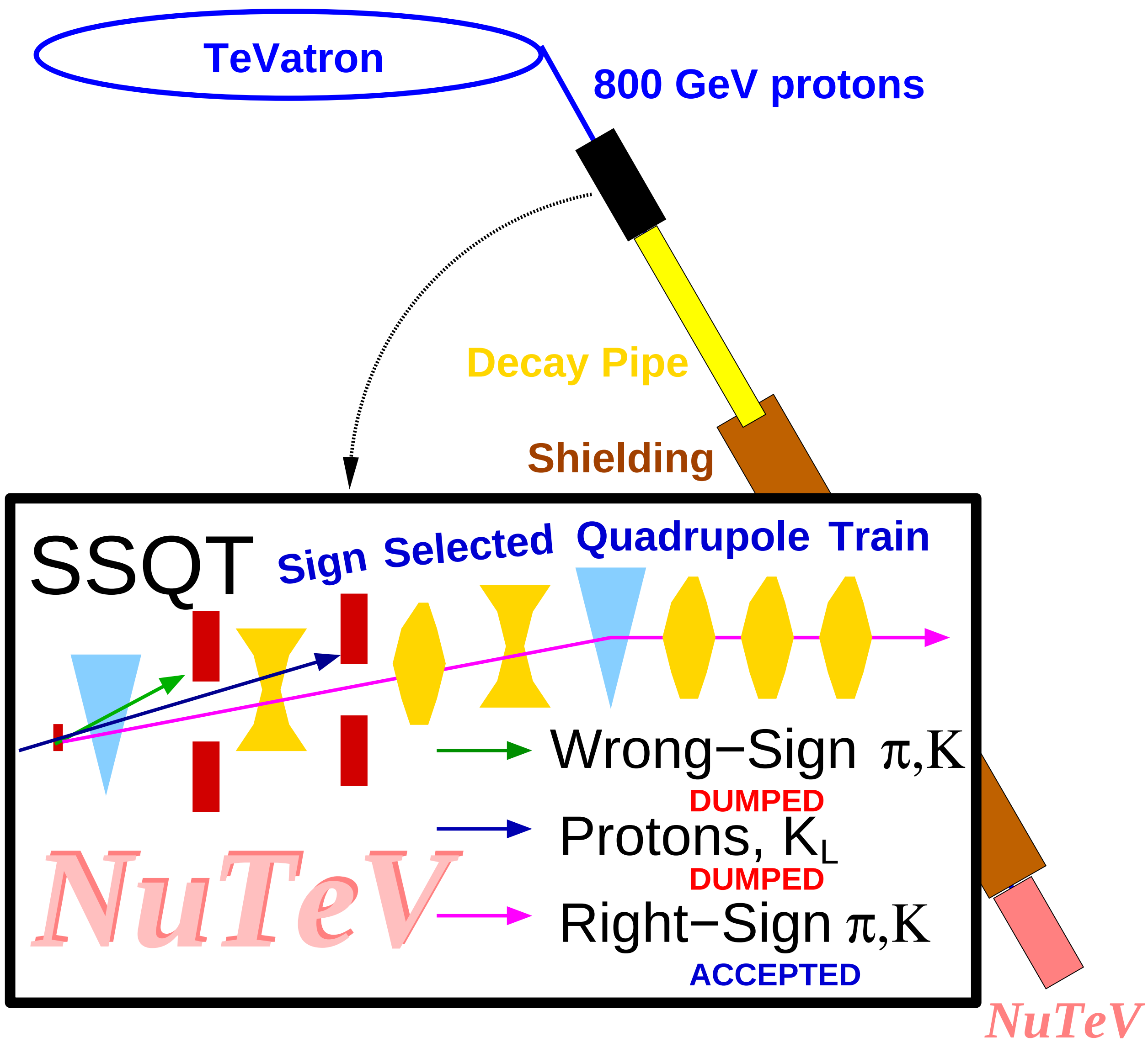
Paschos-Wolfenstein Relation:

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\overline{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\overline{\nu}}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W\right)$$



- R^- manifestly insensitive to sea quarks
  - ↪ Massive quark production enters from d_V quarks only (Cabbibo suppressed and at high x)
  - ↪ Charm, strange sea errors negligible
- Requires Separate ν and $\overline{\nu}$ Beams $\Rightarrow$ NuTeV SSQT

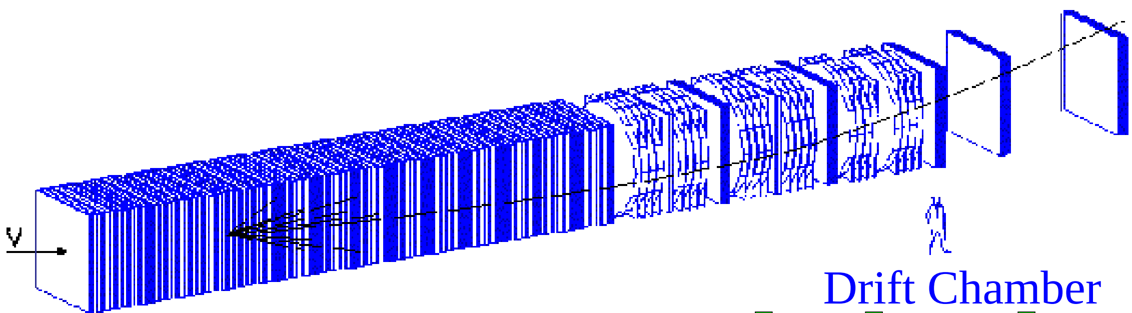
NuTeV Beamline

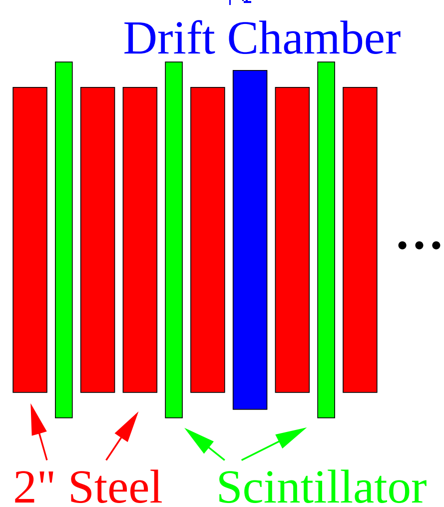


- Beam is almost purely ν or $\overline{\nu}$:
  ($\overline{\nu}$ in ν mode 3×10^{-4}, ν in $\overline{\nu}$ mode 4×10^{-3})
- Beam is $\sim$1.6% electron neutrinos

νN Deep Inelastic Scattering at NuTeV

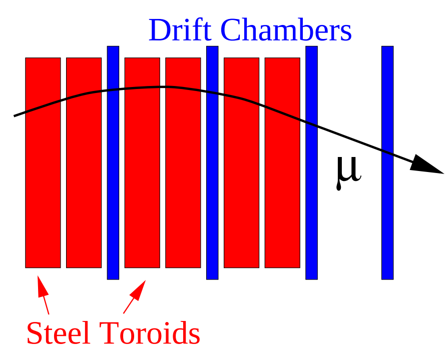
Lab E Detector - Fermilab E815(NuTeV)





Target/Calorimeter:

- 168 Fe plates (3m × 3m × 5.1cm)
- 84 liquid scintillation counters
  Trigger the detector
  Visible energy
  Neutrino interaction point
  Event length
- 42 drift chambers
  Localized transverse shower position



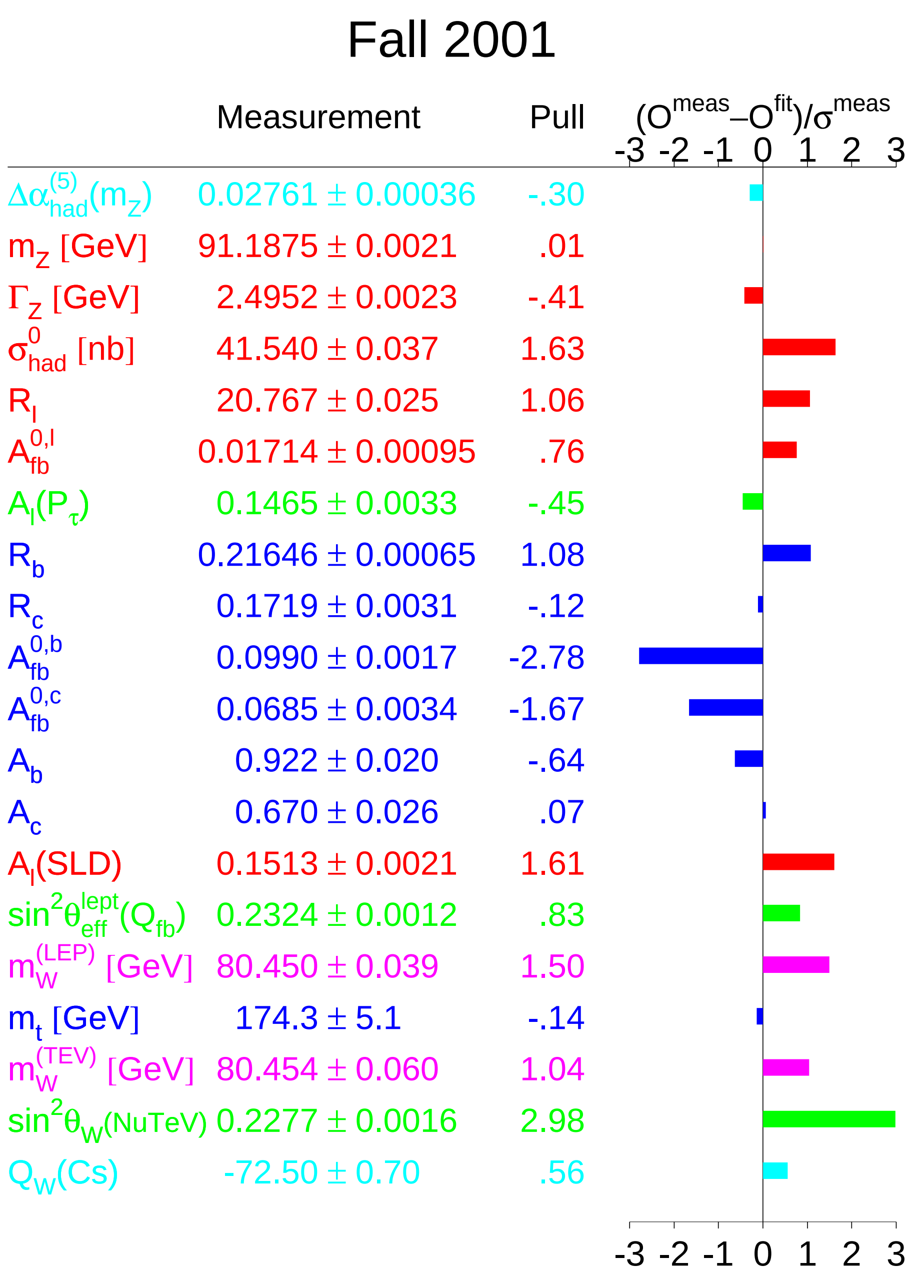
Toroidal Spectrometer:

- 15kG field ($P_T = 2.4\, GeV/c$)

Continuous Test Beam: interspersed with ν beam

- Hadron, muon and electron beams
  Map toroid and calorimeter response

SM Fit with NuTeV $\sin^2\theta_W$



(Courtesy M. Grunewald, LEPEWWG)

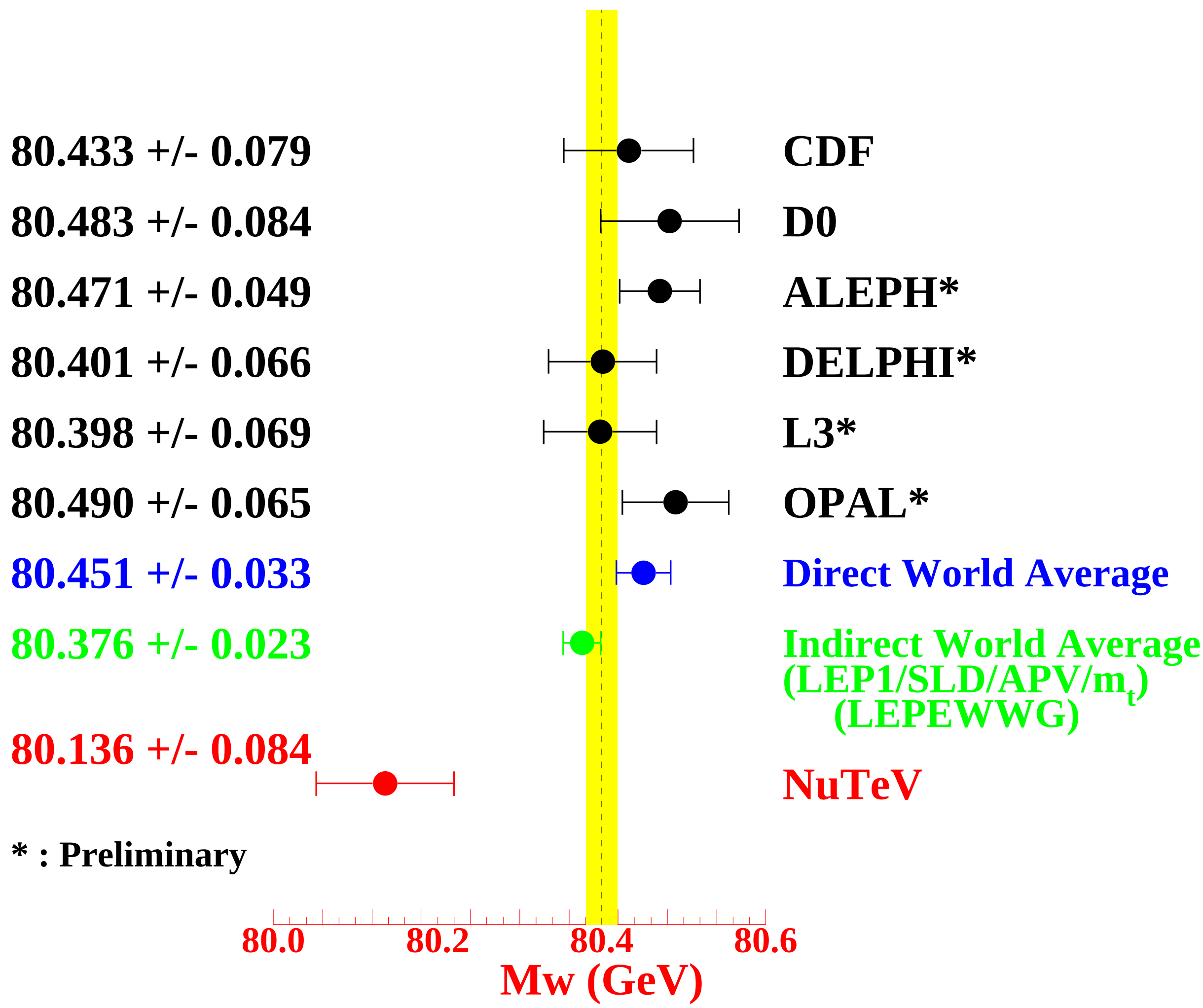
Without NuTeV: $\chi^2/\mathrm{dof} = 21.5/14$, probability of 9.0%

With NuTeV: $\chi^2/\mathrm{dof} = 30.5/15$, probability of 1.0%

Upper m_{Higgs} limit weakens slightly

Comparison with M_W

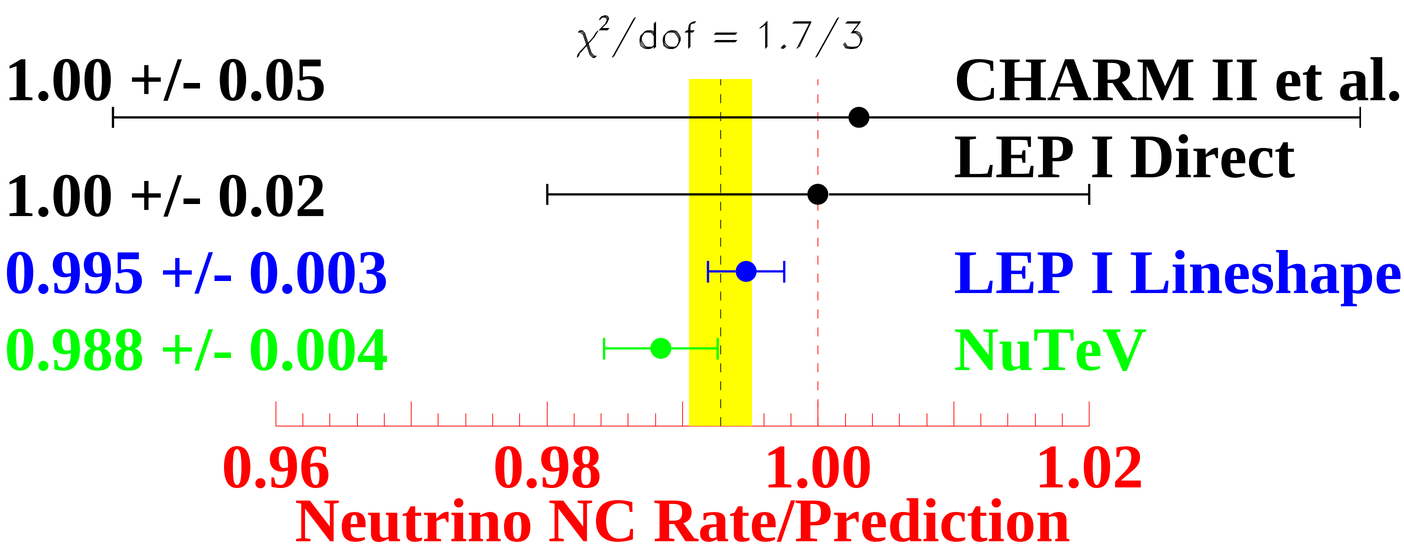
$$\sin^2\theta_W^{(\mathrm{on-shell})} \equiv 1 - \frac{M_W^2}{M_Z^2}$$



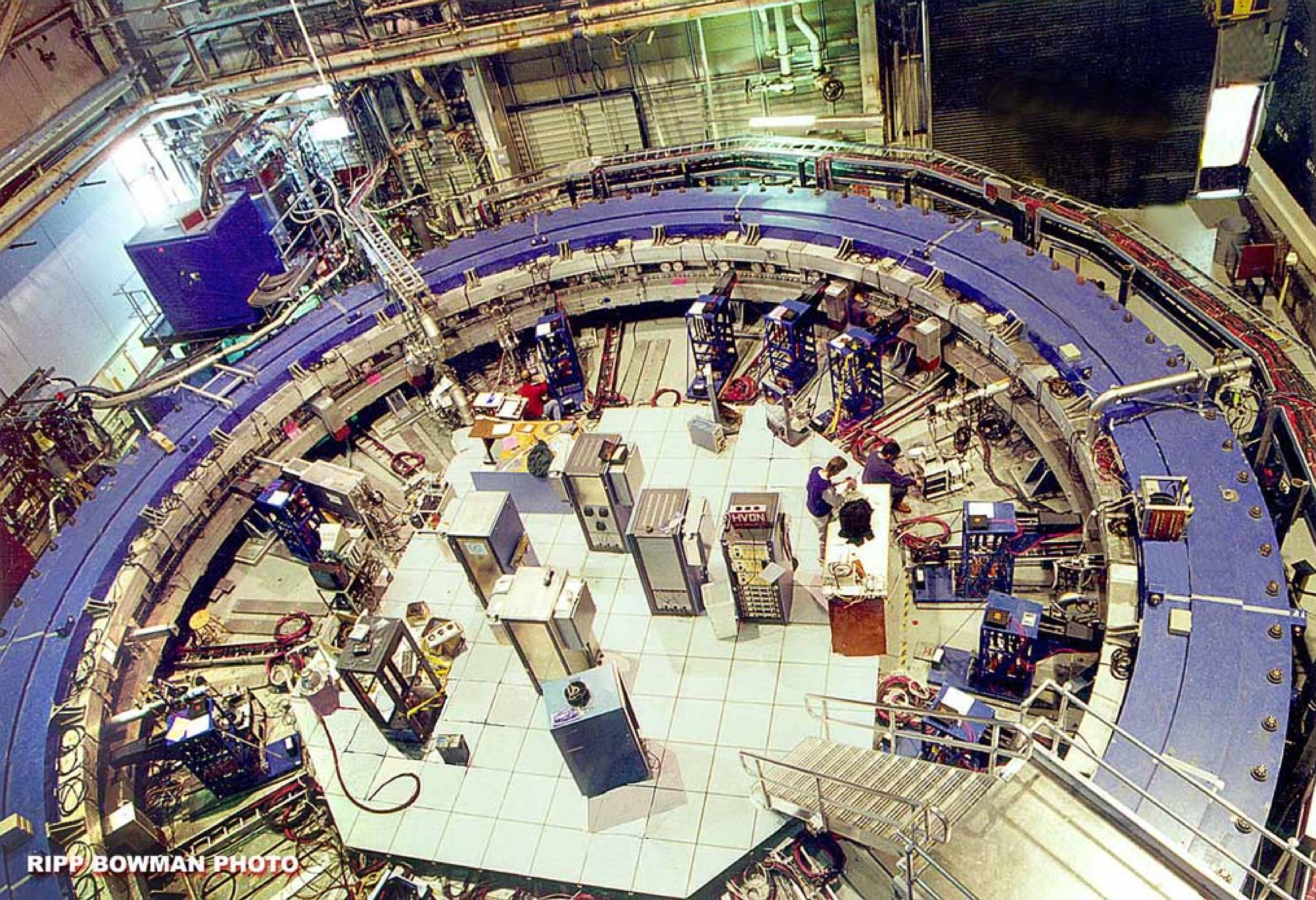
- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of M_W
- More inconsistent with direct M_W than other data

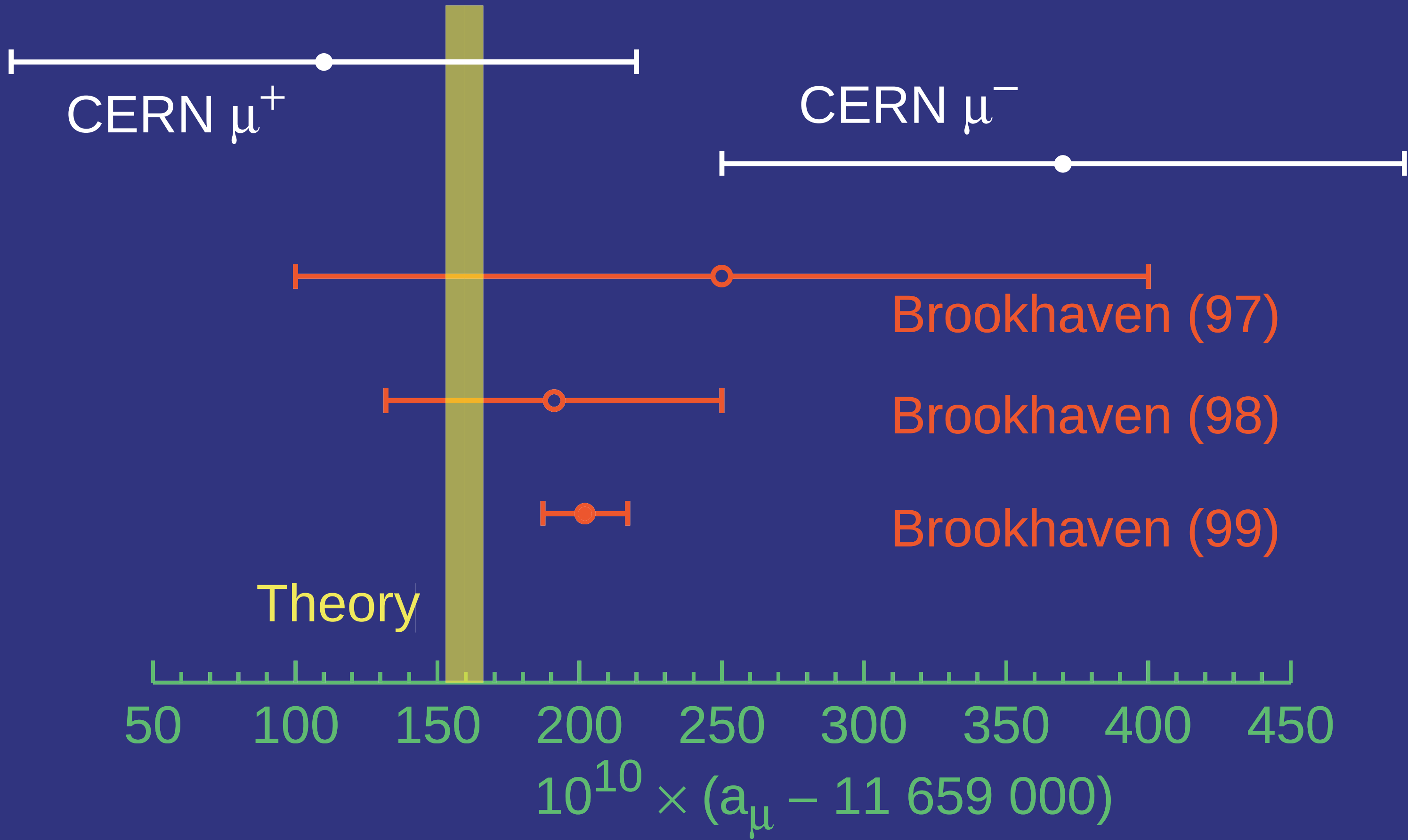
Neutral Current ν Interactions

- LEP I measures Z lineshape and decay partial widths to infer the "number of neutrinos"
  - $\hookrightarrow$ Their result is $N_\nu = 3\frac{\Gamma_{\rm exp}(Z\to\nu\overline{\nu})}{\Gamma_{\rm SM}(Z\to\nu\overline{\nu})} = 3\times(0.9947\pm 0.0028)$
  - $\hookrightarrow$ LEP I "direct" partial width $(\nu\nu\gamma) \Rightarrow N_\nu = 3\times(1.00\pm0.02)$
- $\overset{(-)}{\nu}_\mu e^- \to \overset{(-)}{\nu}_\mu e^-$ scattering (CHARM II *et al.*)
  - $\hookrightarrow$ PDG fit: $g_V^2 + g_A^2 = 0.259\pm0.014$, cf. 0.258 predicted
- NuTeV can fit for a deviation in $\nu\&\overline{\nu}$ NC rate
  - $\hookrightarrow$ $\rho_0^2 = 0.9884 \pm 0.0026(\text{stat}) \pm 0.0032(\text{syst})$

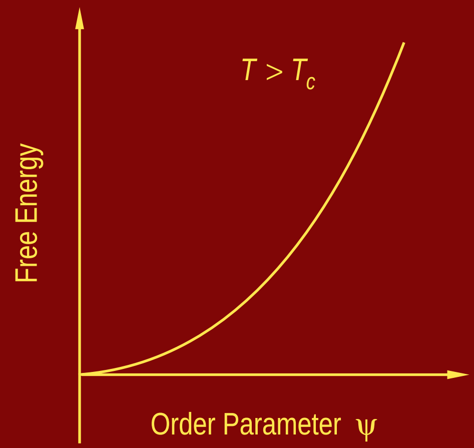


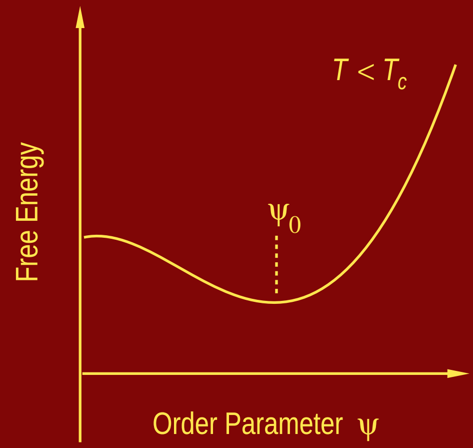
- In this interpretation, NuTeV confirms and strengthens LEP I indications of "weaker" neutrino neutral current
  - $\hookrightarrow$ NB: This is not a unique or model-independent interpretation!


RIPP BOWMAN PHOTO


CERN μ^+
CERN μ^-
Brookhaven (97)
Brookhaven (98)
Brookhaven (99)
Theory
50
100
150
200
250
300
350
400
450
$10^{10} \times (a_\mu - 11\,659\,000)$

Analogy to superconductivity sets M_W, M_Z





Meissner effect: EM fields disturb condensate of Cooper pairs

Weak bosons disturb Higgs condensate, acquire masses:

$$M_W^2 = \frac{g^2 v^2}{2} = \frac{\pi\alpha}{G_F\sqrt{2}\sin^2\theta_W}$$

$$M_Z^2 = \frac{M_W^2}{\cos^2\theta_W}$$

EW scale is $v = \left(G_\mathrm{F}\sqrt{2}\right)^{-\frac{1}{2}} \approx 246$ GeV

Disturbing EW condensate may generate fermion mass

$\boxed{\text{EWSB is necessary, not sufficient}}$

Standard model: each fermion mass $\Rightarrow$ new, *unknown* Yukawa coupling

$$\mathcal{L}^{(e)}_{\text{Yukawa}} = -\zeta_e \left[\overline{\mathsf{R}}(\phi^\dagger \mathsf{L}) + (\overline{\mathsf{L}}\phi)\mathsf{R} \right] .$$

$$\boxed{m_e = \zeta_e v/\sqrt{2}}$$

All fermion masses $\sim$ physics beyond the standard model!

$$\zeta_t \approx 1 \qquad \zeta_e \approx 3 \times 10^{-6} \qquad \zeta_\nu \approx 10^{-10} \text{ ??}$$

What accounts for the range and values of the Yukawa couplings?

There may be *other sources* of neutrino mass

Best hope until now:

Unified theories: pattern of fermion masses *simplifies* on high scales

Yukawa couplings offer the possibility of CP violation ...

CONSIDER

$$-\mathcal{L}^{(d)}_{Yukawa} = \underbrace{}_{}\zeta^{d}_{ij}\, \underbrace{\bar{L}_{qi}\, \varphi\, R_{dj}}_{} + \zeta^{d\,*}_{ij}\, \underbrace{\bar{R}_{dj}\, \varphi^{+} L_{di}}_{}$$

CP INTERCHANGES

IF $\zeta^{d}_{ij} \neq \zeta^{d\,*}_{ij}$,

CP IS NOT A SYMMETRY OF $\mathcal{L}_{Yukawa}$

THE CP VIOLATION WITHIN THE SM (ARISING FROM THE QUARK MIXING MATRIX / YUKAWA COUPLINGS) IS ITSELF A WINDOW ON PHYSICS BEYOND THE STANDARD MODEL.

ν_{solar} **News**

$$\phi^{\rm CC}_{\rm SNO}(\nu_e) = 1.75 \pm 0.07\ ({\rm stat.})^{+0.12}_{-0.11}\ ({\rm sys.}) \pm 0.05\ ({\rm th.}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}$$

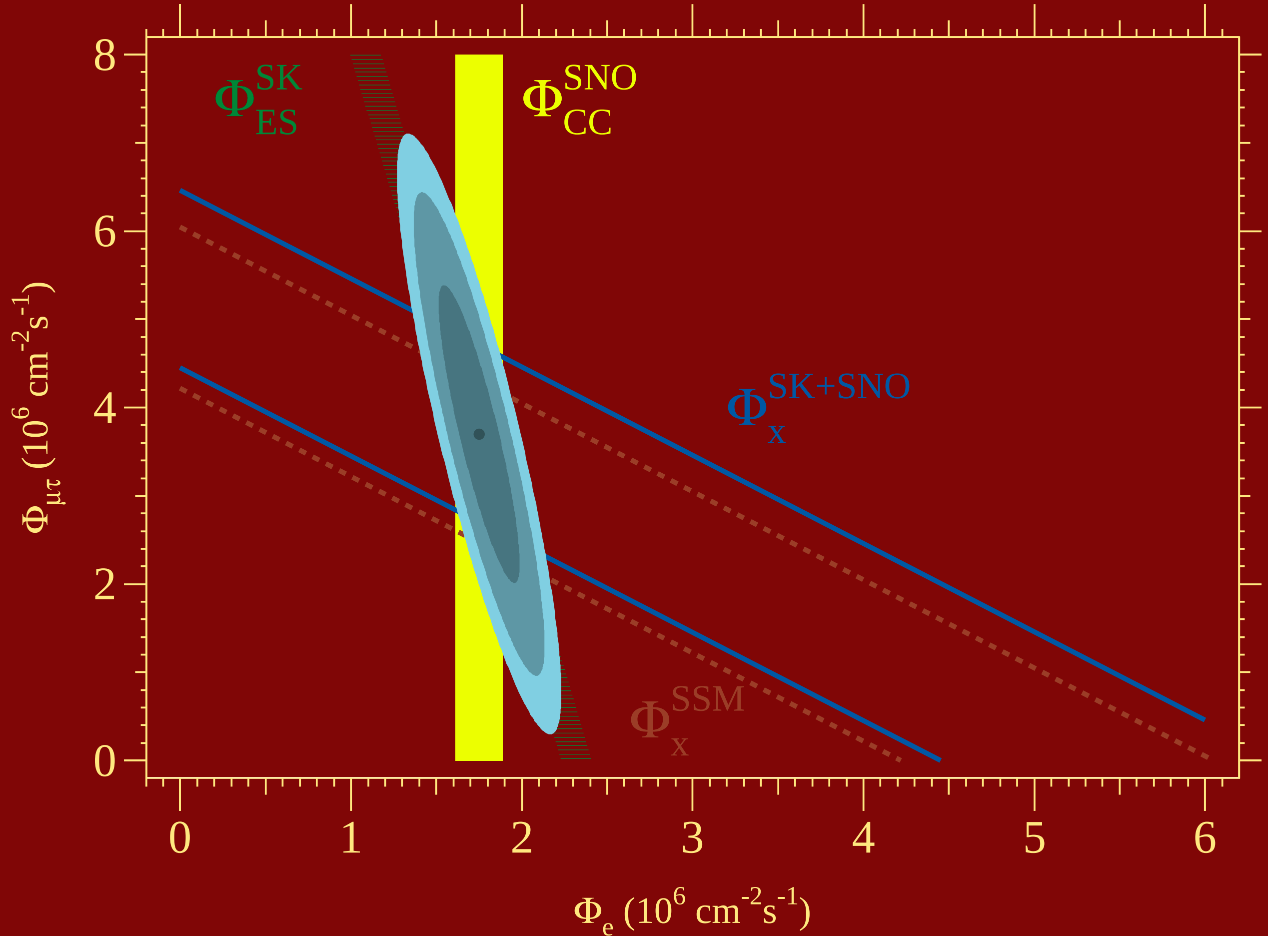
$$\phi^{\rm ES}_{\rm SNO}(\nu_x) = 2.39 \pm 0.0.34\ ({\rm stat.})^{+0.16}_{-0.14}\ ({\rm sys.}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}$$

$$\phi^{\rm ES}_{\rm Super-K}(\nu_x) = 2.32 \pm 0.03\ ({\rm stat.})^{+0.08}_{-0.07}\ ({\rm sys.}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}$$

$$\phi^{\rm ES}_{\rm Super-K}(\nu_x) - \phi^{\rm CC}_{\rm SNO}(\nu_e) = 0.57 \pm 0.17 \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}$$

$$\boxed{\Longrightarrow \nu_\mu \text{ and } \nu_\tau \text{ arrive at Earth (at } 3.3\sigma)}$$

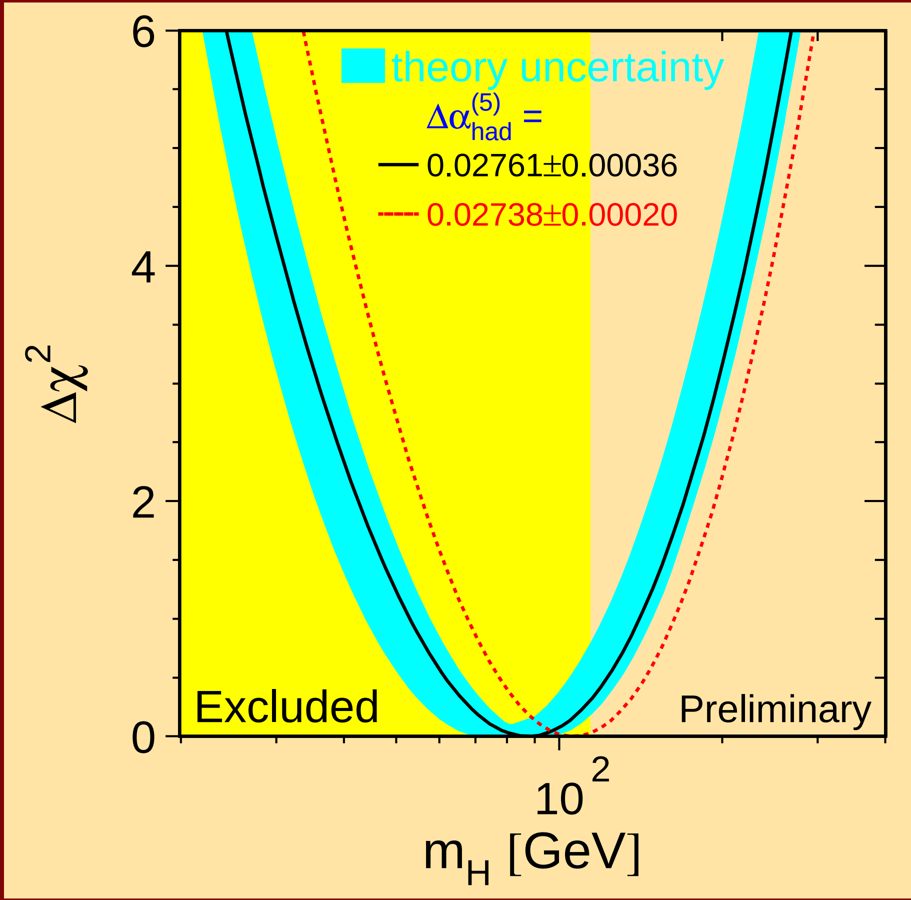
Combined SNO + Super-K ^{8}B Neutrinos



$$\phi(\nu_{\mu\tau}) \quad = \quad 3.69 \pm 1.13 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

$$\phi(\nu_{\text{active}}) \quad = \quad 5.44 \pm 0.99 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

Quantum corrections suggest the Higgs-boson mass . . .



. . . within the standard electroweak theory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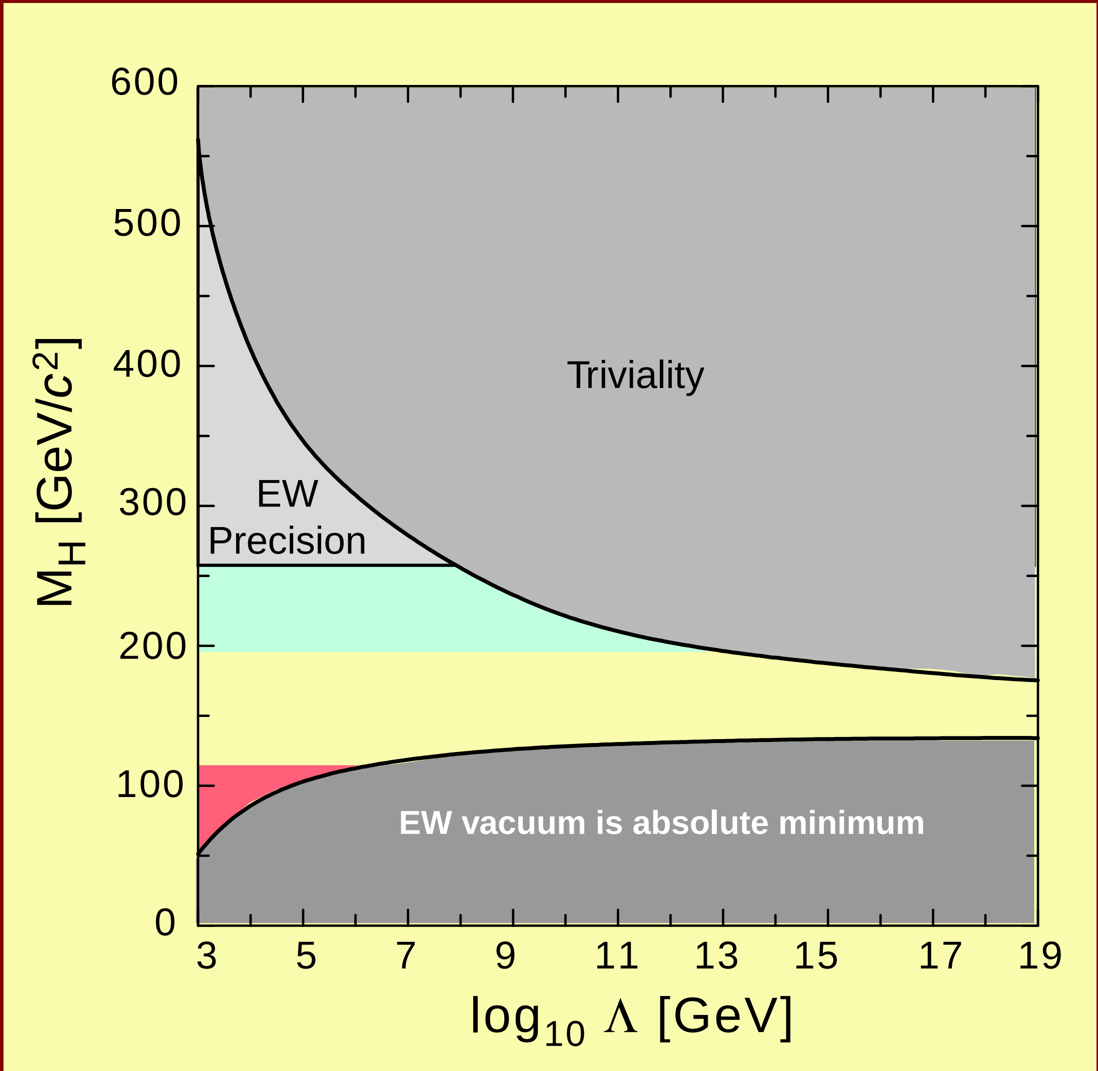
A light Higgs boson hints new physics nearby



Elementarity

- ▷ Are quarks and leptons structureless?

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Symmetry

▷ Electroweak symmetry breaking and the 1-TeV scale

▷ Origin of gauge symmetries

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Unity

▷ Coupling constant unification

▷ Unification of quarks and leptons (new forces!); of constituents and force particles

▷ Incorporation of gravity

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▷ Fermion masses and mixings; CP violation; neutrino oscillations

▷ What makes an electron an electron and a top quark a top quark?

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Topography

▷ What is the fabric of space and time? . . . the origin of space and time?

The Vacuum Energy Problem (Veltman)

Higgs potential

$$V(\varphi^\dagger\varphi) = \mu(\varphi^\dagger\varphi) + |\lambda|(\varphi^\dagger\varphi)^2$$

At the minimum

$$\langle\varphi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \simeq \begin{pmatrix} 0 \\ 176\text{ GeV} \end{pmatrix},$$

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0$$

IDENTIFY $M_H^2 = -2\mu^2$.

Higgs potential contributes a field-independent constant energy density

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \gtrsim \underbrace{10^8 \text{ GeV}^4}_{M_H \gtrsim 100 \text{ GeV}}$$

Observed Vacuum Energy Density

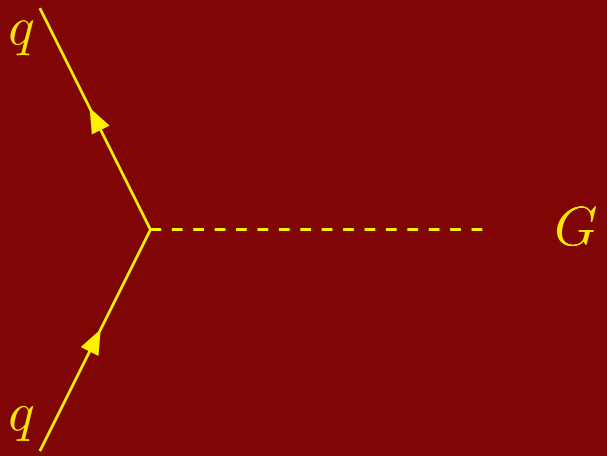
$$\varrho_{vac} \lesssim 10^{-46} \text{ GeV}^4$$

MISMATCH BY 54 ORDERS OF MAG.

How to zero ϱ_H?

Natural to neglect gravity in particle physics

$$G_{\text{Newton}} \textit{ small } \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19}\ \text{GeV} \textit{ large}$$



$$\sim \frac{E}{M_{\text{Planck}}}$$

$$\text{Estimate } B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$$

300 years after Newton: Why *is* gravity weak?

Conventional approach: change electroweak theory to understand why $M_H, v \ll M_{\rm Planck}$

Resolve the hierarchy problem: *EXTEND THE STANDARD MODEL*

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \left\{ \begin{array}{c} \text{composite Higgs boson} \\ \text{technicolor / topcolor} \\ \text{supersymmetry} \\ \ldots \end{array} \right.$$

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Novel speculation: change gravity to understand why $M_{\text{Planck}} \gg v$

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Novel speculation: change gravity to understand why $M_{\text{Planck}} \gg v$

$\triangleright$ String theory: extra dimensions assumed $R_{\text{ed}} \simeq 1/M_{\text{Planck}} \simeq 10^{-35}$ cm

Conventional approach: **change electroweak theory**
to understand why $M_H, v \ll M_{\text{Planck}}$

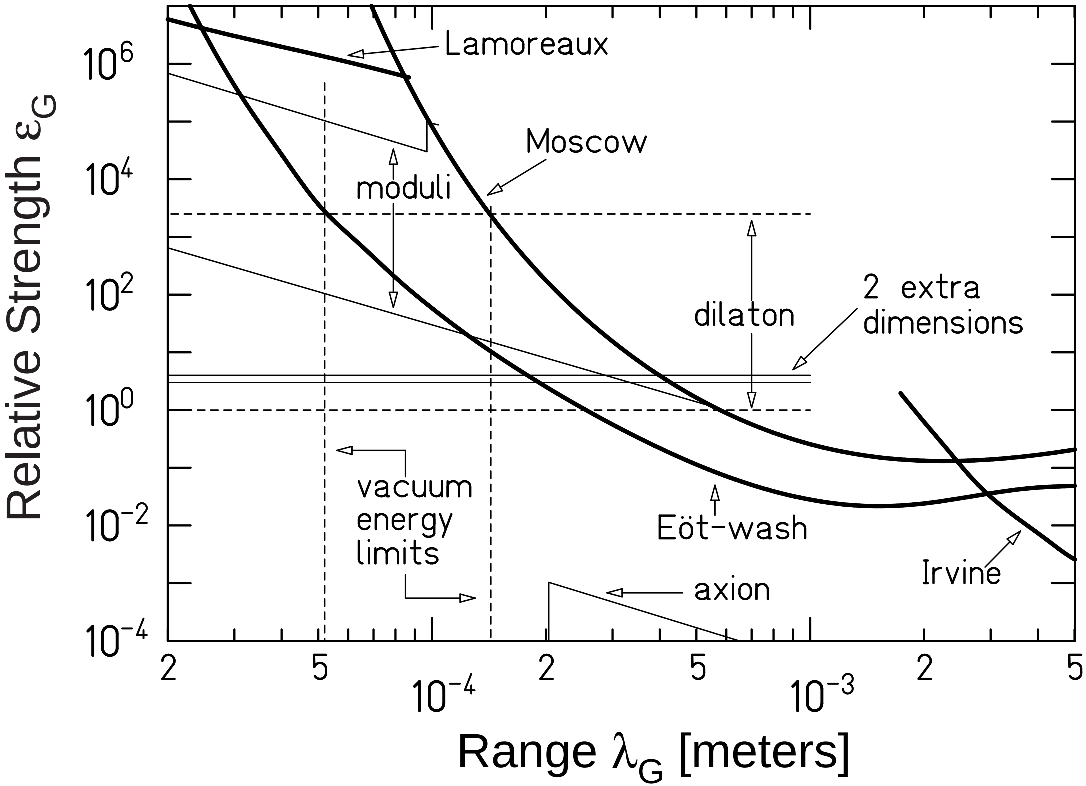
Resolve the hierarchy problem: *EXTEND THE STANDARD MODEL*

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \begin{cases} \text{composite Higgs boson} \\ \text{technicolor / topcolor} \\ \text{supersymmetry} \\ \ldots \end{cases}$$

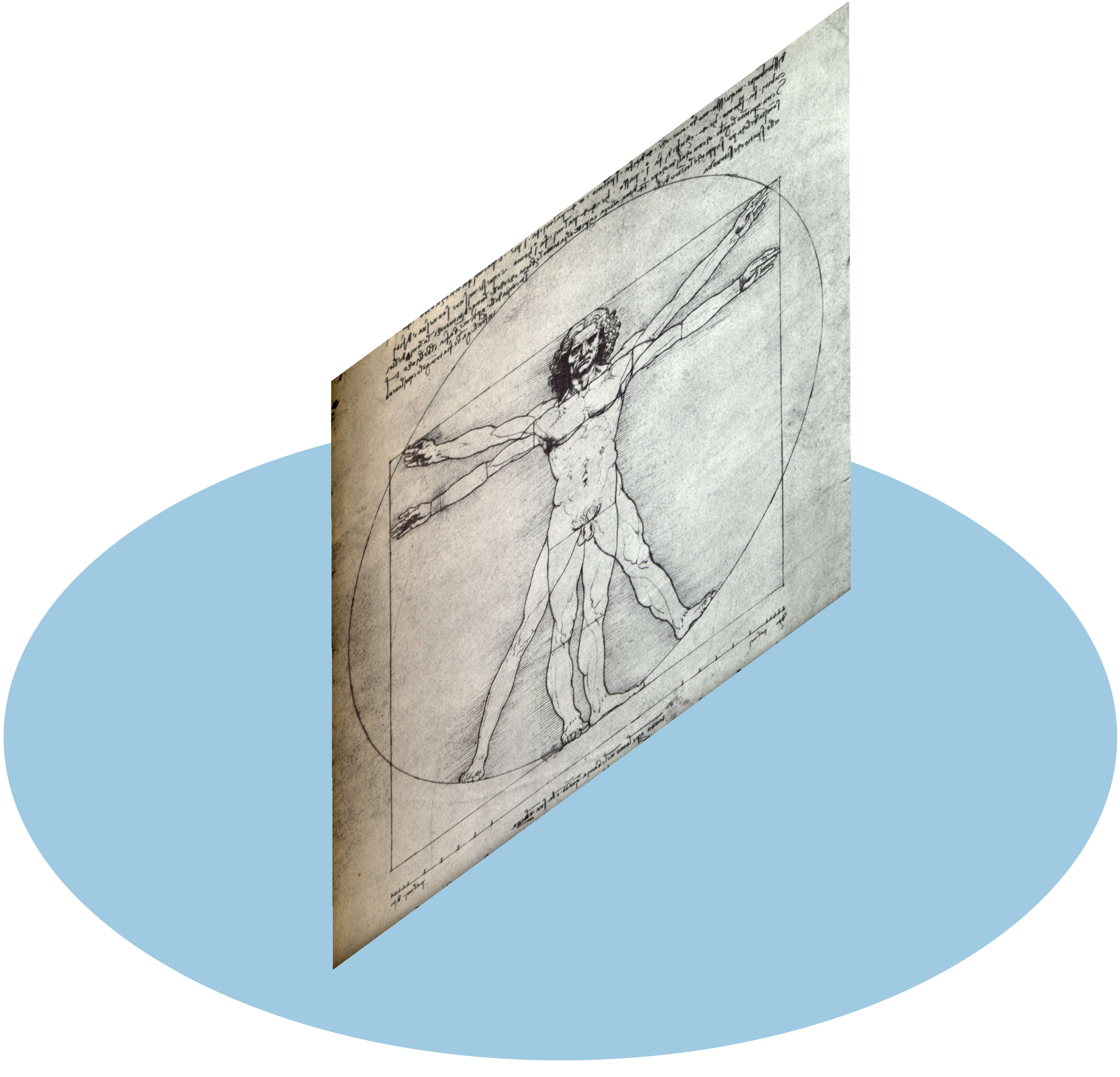
Novel speculation: **change gravity**
to understand why $M_{\text{Planck}} \gg v$

- ▷ String theory: extra dimensions assumed $R_{\text{ed}} \simeq 1/M_{\text{Planck}} \simeq 10^{-35}$ cm
- ▷ Gravity follows Newtonian force law down to $\lesssim 1$ mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}}\rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_{\text{G}} \exp(-r_{12}/\lambda_{\text{G}})\right]$$



Lamoreaux
Moscow
moduli
dilaton
2 extra dimensions
vacuum energy limits
Eöt-wash
axion
Irvine
Relative Strength ε_G
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
2
5
10^{-4}
2
5
10^{-3}
2
5
Range λ_G [meters]



IF GRAVITY PROPAGATES IN EXTRA DIM,
dimensional analysis changes (Gauss)

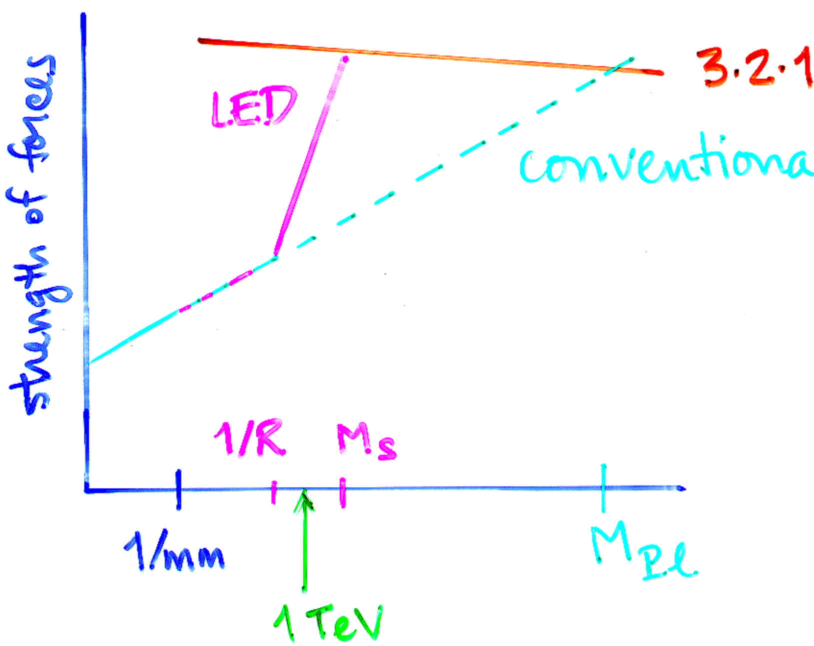
n extra dim., radius R $\Rightarrow$

$$G_N \sim M_{Pl}^{-2} \sim M_s^{-n-2} R^{-n}$$

If $M_s \sim 1$ TeV, $R \lesssim 1$ mm for $n \geq 2$

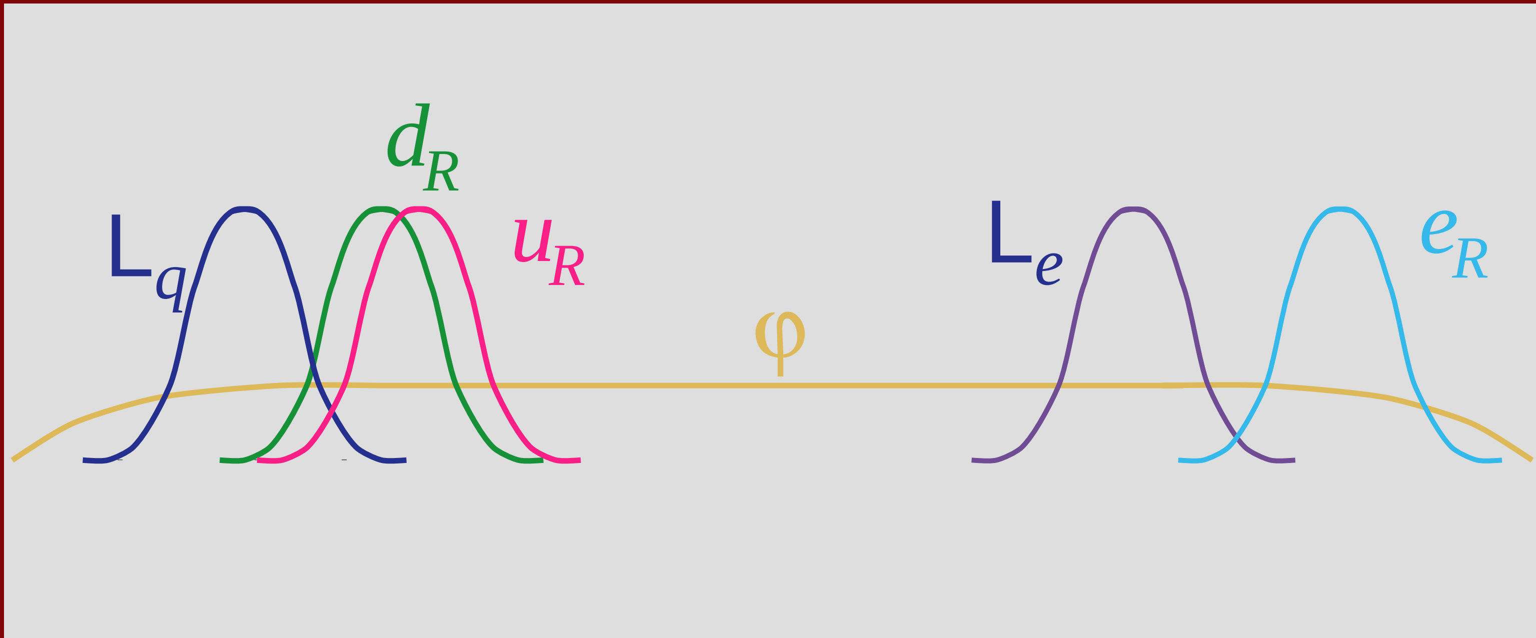
$$M_{Pl} = M_s (M_s R)^{n/2}$$

would mean that M_{Pl} results from a false extrapolation



Gravity's true scale could be near EW scale.. (Subversive idea)

Might Extra Dimensions Explain the Range of Fermion Masses?



Arkani-Hamed, Schmaltz, and Mirabelli:

Different fermions ride different tracks in the 5$^{\text{th}}$ dimension

Small offsets in the new coordinate $\Rightarrow$ exponential differences in masses

The Great Lesson of Science in the Twentieth Century

The human scale is not privileged for understanding Nature . . .

and may even be disadvantaged

In a decade or two, we can hope to . . .

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, . . .)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

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. . . and to learn the right questions to ask

A Decade of Discovery Ahead

In the midst of a revolution in our conception of Nature, we deal with fundamental questions about our world, including

- Are the quarks and leptons elementary or composite?
- What are the symmetries of Nature, and how are they hidden from us?
- Are there new forms of matter, like the superpartners suggested by supersymmetry?
- Are there more fundamental forces?
- What makes an electron an electron and a top quark a top quark?
- What is the dimensionality of spacetime?

Nothing is too wonderful to be true,
if it be consistent with the laws of nature . . .
Experiment is the best test

Michael Faraday

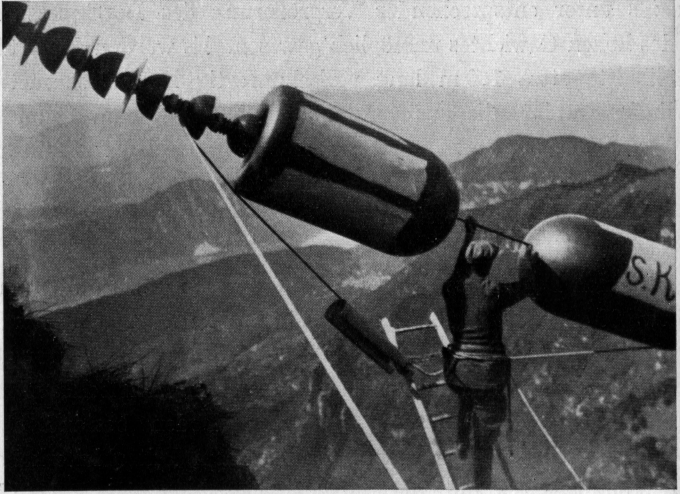

Fig. 2.
Montage der letzten Sprühschutzkörper. Durchmesser 80 cm.

[T]here has been one transforming change over this thousand years. It is the adoption of the scientific method: the commitment to experiment, to test every hypothesis. But it is broader than science. It is the open mind, the willingness in all aspects of life to consider possibilities other than the received truth. It is openness to reason.

—Anthony Lewis, New York *Times*, 12/31/99

On the first emulsions from the Pic du Midi:

"It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion."

—Cecil Frank Powell